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Fluid and electrolyte needs for preparation and recovery from training and competition

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For a person undertaking regular exercise, any fluid deficit that is incurred during one exercise session can potentially compromise the next exercise session if adequate fluid replacement does not occur. Fluid replacement after exercise can, therefore, frequently be thought of as hydration before the next exercise bout. The importance of ensuring euhydration before exercise and the potential benefits of temporary hyperhydration with sodium salts or glycerol solutions are also important issues. Post-exercise restoration of fluid balance after sweat-induced dehydration avoids the detrimental effects of a body water deficit on physiological function and subsequent exercise performance. For effective restoration of fluid balance, the consumption of a volume of fluid in excess of the sweat loss and replacement of electrolyte, particularly sodium, losses are essential. Intravenous fluid replacement after exercise has been investigated to a lesser extent and its role for fluid replacement in the dehydrated but otherwise well athlete remains equivocal.

Keywords: hypohydration, rehydration, water balance, electrolyte balance.

Introduction

The metabolic heat generated by exercise must be dissipated to maintain body temperature within narrow physiological limits. When ambient temperature exceeds skin temperature, heat loss can occur only by evaporation of sweat from the skin surface. Significant rates of sweat production will also occur in a cool environment if the work rate is high. Indeed, sweat rates exceeding $2\ \mathrm{l \cdot h^{-1}}$ can be maintained for many hours by trained and acclimated individuals exercising in warm, humid conditions. This is demonstrated by the body mass losses in marathon runners, which can range from about 1–6% (0.7–4.2 kg of body mass for a 70-kg man) at low (10°C) ambient temperatures to more than 8% (5.6 kg) in warmer conditions (Maughan and Shirreffs, 1998). With exercise in a warm environment, 30–40% of total body water may be turned over in a single day, but a deficit of even half of that amount will result in serious disability or even death (Adolph *et al.*, 1947).

When sweating takes place, the free exchange of water among body fluid compartments ensures that the water content of sweat is derived from all compartments, with the distribution being influenced by sweat rate, sweat composition and total water and electrolyte loss. Sodium is the primary cation lost in sweat, with typical concentrations of about $40\text{–}60\ \mathrm{mmol \cdot l^{-1}}$, compared with about $4\text{–}8\ \mathrm{mmol \cdot l^{-1}}$ for potassium (Maughan and Shirreffs, 1998). Given the higher sodium loss and the distribution of these cations between the body water compartments, the primary water loss is likely to be from the extracellular space.

It is well documented that even small body water deficits, incurred before (Armstrong *et al.*, 1985; Sawka, 1992) or during (Cheuvront *et al.*, 2003) exercise can significantly impair aerobic exercise performance, especially in the heat (Sawka, 1992; Cheuvront *et al.*, 2003). Armstrong *et al.* (1985) studied participants in track races over 1500, 5000 and 10,000 m after reducing body mass by 2% using a diuretic. The time to complete these races was increased by 0.16, 1.31 and 2.62 min (3.4, 6.7 and 6.7%), respectively, relative to their finishing time when euhydrated.

The plasma volume decrease that accompanies dehydration may be of particular importance in

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influencing work capacity; blood flow to the muscles must be maintained at a high level during exercise to supply oxygen and substrates, but a high blood flow to the skin is also necessary to transfer heat to the body surface where it can be dissipated. Hypohydration is associated with higher cardiovascular strain and impaired thermoregulation and with loss of the protection conferred by acclimation (Sawka, 1992). Loss of intracellular volume may be particularly important during recovery, however, in the light of the emerging evidence of a role for cell volume in the regulation of metabolism. A reduced intracellular volume can reduce rates of glycogen and protein synthesis and a high cell volume can stimulate these processes (Lang *et al.*, 1995).

Pre-exercise hydration

For a person undertaking regular exercise, any fluid deficit that is incurred during one exercise session can potentially compromise the next exercise session if adequate fluid replacement does not occur. Fluid replacement after exercise can frequently be thought of as hydration before the next exercise bout.

However, in addition to this, the issue of pre-exercise hyperhydration has been investigated in the last decade. In a healthy individual, the kidneys excrete any excess body water; therefore, ingesting excess fluid before exercise is generally ineffective at inducing pre-exercise hyperhydration. To overcome this, ingestion of either salt or glycerol solutions has been investigated as possible means of minimizing the usual diuresis when a euhydrated individual ingests excess water. A limited amount of temporary hyperhydration occurs when drinks with high concentrations ($>100\ \text{mmol}\cdot\text{l}^{-1}$) of sodium are ingested (Fortney *et al.*, 1984), but there are problems of palatability with high sodium drinks and nausea and vomiting with salt tablets. Glycerol has been shown to be an effective hyperhydrating agent. Several studies have suggested that ingesting 1.0–1.5 g $\text{glycerol}\cdot\text{kg}^{-1}$ BM (where BM = body mass), together with a large volume of water, can significantly increase water retention and improve cycling time to fatigue (Riedesel *et al.*, 1987; Lyons *et al.*, 1990; Montner *et al.*, 1996; Hitchins *et al.*, 1999). Others (Latzka *et al.*, 1997, 1998) have observed no differences in thermoregulatory or performance parameters. In addition, there have been a number of reports of side-effects with glycerol ingestion (Latzka and Sawka, 2000) that preclude this technique as a method of pre-exercise hyperhydration. In fact, a recent review of hyperhydration and glycerol came to the conclusion that 'if euhydration is maintained during exercise-heat stress then [pre-exercise] hyperhydration appears to have no meaningful advantage' (Latzka and Sawka, 2000).

However, the practice of drinking in the hours before exercise is effective at ensuring euhydration before exercise if there is any possibility that slight hypohydration is present. The American College of Sports Medicine (1996) practical recommendation of ingesting 400–600 ml of water 2 h before exercise to allow the kidneys time to regulate total body water volume has been used to help ensure euhydration before laboratory studies. The resulting data of urine osmolality or specific gravity and serum osmolality or hormone measures indicate that the practice is generally effective at achieving euhydration in such circumstances (Shirreffs *et al.*, 1996; Shirreffs and Maughan, 1998).

Post-exercise rehydration

The main factors influencing the post-exercise rehydration process are the volume and composition of the fluid consumed. The volume consumed will be influenced by many factors, including the palatability of the drink and its effects on the thirst mechanism, although with a conscious effort some people can still drink large quantities of an unpalatable drink when they are not thirsty. The ingestion of solid food, and the composition of that food, may also be important, but there are many circumstances in which solid food is avoided between exercise sessions or immediately after exercise.

Beverage composition

Sodium

Plain water is not the ideal post-exercise rehydration beverage when rapid and complete restoration of fluid balance is necessary and where all intake is in liquid form. Early studies in the area (e.g. Costill and Sparks, 1973; Nielsen *et al.*, 1986) established that the high urine flow that followed ingestion of large volumes of electrolyte-free drinks did not allow individuals to remain in positive fluid balance for more than a very short time. They also established that the plasma volume was better maintained when electrolytes were present in the fluid ingested, an effect attributed to the presence of sodium in the drinks. In none of these studies, however, could the mechanism of the action be identified, as the drinks used differed from each other in several respects, including flavouring, carbohydrate and electrolyte content.

The first studies to investigate the mechanisms of post-exercise rehydration showed that the ingestion of large volumes of plain water after exercise-induced dehydration resulted in a rapid fall in plasma osmolality and sodium concentration (Nose *et al.*, 1988a), leading to a prompt and marked diuresis caused by a rapid return to control levels of plasma renin activity and aldosterone (Nose *et al.*, 1988b). Therefore, the replacement of sweat losses with plain water will, if the volume ingested is sufficiently large, lead to haemodilution. The fall in plasma osmolality and sodium concentration that occurs reduces the drive to drink and stimulates urine output (Nose *et al.*, 1988a) and has potentially more serious consequences such as hyponatraemia.

Sodium is the major ion in the extracellular fluid, thus it is intuitive that sweat sodium losses should be replaced if plasma volume is to be restored or maintained. In a systematic investigation of the relationship between whole-body sweat sodium losses and the effectiveness of beverages with different sodium concentrations in restoring fluid balance, Shirreffs and Maughan (1998) showed that, provided that an adequate volume is consumed, euhydration is achieved when the sodium intake is greater than the sweat sodium loss, although, as discussed below, not all studies have reported similar findings (Mitchell *et al.*, 2000). However, to investigate this properly it is important that the study design allows for sufficient time for drink-induced diuresis to occur once drinking is finished. Generally a minimum of 2 h is required after drinking a bolus of fluid to allow sufficient time for any significant renal excretion of water to occur.

The addition of sodium to a rehydration beverage is therefore justified on the basis that sodium is lost in sweat and must be replaced to achieve full fluid balance restoration. It has been demonstrated that a drink's sodium concentration is more important than its osmotic content for increasing plasma volume after dehydration (Greenleaf *et al.*, 1998). Sodium also stimulates glucose absorption in the small intestine via the active co-transport of glucose and sodium, which creates an osmotic gradient that acts to promote net water absorption. This sodium can either be consumed with the drink or be secreted by the intestine. Furthermore, sodium has been recognized as an important ingredient in rehydration beverages by an inter-association task force on exertional heat illnesses (American Physiological Society, 2003) because sodium plays a role in the aetiology of exertional heat cramps, exertional heat exhaustion and exertional hyponatraemia (Armstrong and Casa, 2003).

Potassium

Potassium is the major ion in the intracellular fluid. Potassium may therefore be important in achieving rehydration by aiding the retention of water in the intracellular space. An initial study investigating this (Yawata, 1990) thermally dehydrated rats by approximately 9% of their body mass and then gave them free access to rehydration solutions consisting of isotonic sodium chloride (NaCl), isotonic potassium chloride (KCl) or tap water. While the rats drank substantially more NaCl than KCl, they urinated only slightly more after consuming the NaCl. The best rehydration was achieved with the NaCl treatment. In this study, whole-body net fluid balance was influenced by the rats' taste preferences for the beverages, in addition to the effects of the drinks on urine production. With the NaCl drink, 178% of the extracellular volume losses were restored, compared with only 50% with the KCl drink. The intracellular volume recovery did not differ significantly between groups but did tend to be higher in the KCl group. Yawata suggested that, in the extracellular space, restoring sodium concentration is more important than volume restoration but volume restoration has priority in the intracellular fluid. Also, the role of potassium in restoring intracellular volume is more modest than sodium's role in restoring extracellular volume.

This topic was subsequently investigated in men dehydrated by approximately 2% of body mass by exercise who then ingested a glucose beverage (90 $mmol \cdot l^{-1}$), a sodium-containing beverage (NaCl 60 $mmol \cdot l^{-1}$), a potassium-containing beverage (KCl 25 $mmol \cdot l^{-1}$) or a beverage containing all three components (Maughan *et al.*, 1994). All drinks were consumed in a volume equivalent to the mass loss, but a smaller volume of urine was excreted following rehydration when each of the electrolyte-containing beverages was ingested (about 250–300 ml) compared with the electrolyte-free beverage (a mean volume of 577 ml). Therefore, there was no difference in the fraction of ingested fluid retained 6 h after finishing drinking the drinks that contained electrolytes. This may be because the beverage volume consumed was equivalent to the volume of sweat lost and, because of the ongoing urine losses, the participants were dehydrated throughout the entire study, even immediately after the drinking period. The volumes of urine excreted were close to basal values and significant further reductions in output may not have been possible when both sodium and potassium were ingested. An estimated plasma volume decrease of 4.4% was observed with dehydration over all trials, but the rate of recovery was slowest when the KCl beverage was consumed.

Potassium, therefore, may be important in enhancing rehydration by aiding intracellular rehydration, but further investigation is required to provide conclusive evidence.

Other electrolytes

The importance of including magnesium in sports drinks has been the subject of much discussion. Magnesium is lost in sweat and many believe that this causes a reduction in plasma magnesium concentrations, which has been implicated in muscle cramp. Even though there can be a decline in plasma magnesium concentration during exercise, it is most likely to be due to compartmental fluid redistribution rather than to sweat loss. There does not, therefore, appear to be any good reason for including magnesium in post-exercise rehydration and recovery sports drinks.

Sodium is the most important electrolyte in terms of recovery after exercise. Without its replacement, water retention is hampered. Potassium is also included in sports drinks in concentrations similar to those in sweat. Although there is strong evidence for the inclusion of sodium, this is not the case with potassium. There is no evidence for the inclusion of any other electrolytes.

Beverage volume

Obligatory urine losses persist after exercise, even in the dehydrated state, because of the need for elimination of metabolic waste products. Respiratory and transcutaneous losses also contribute to an ongoing loss of water from the body. The volume of fluid consumed after exercise-induced or thermal sweating must therefore be greater than the volume of sweat lost if effective rehydration is to be achieved. This contradicts earlier recommendations that after exercise athletes should match fluid intake exactly to the measured body mass loss. Shirreffs *et al.* (1996) examined the effect of drink volumes equivalent to 50, 100, 150 and 200% of the sweat loss consumed after exercise-induced dehydration equivalent to approximately 2% of body mass. To investigate the possible interaction between beverage volume and its sodium content, a relatively low sodium drink (23 $mmol \cdot l^{-1}$) and a moderately high sodium drink (61 $mmol \cdot l^{-1}$) were compared. Participants were unable to return to euhydration when they consumed a volume equivalent to, or less than, their sweat loss, irrespective of the drink composition. When a drink volume equal to 150% of the sweat loss was consumed, participants were slightly hypohydrated 6 h after drinking when the test drink had a low sodium concentration, and they were in a similar condition when they drank the same beverage in a volume of twice their sweat loss. With the high sodium drink, enough fluid was retained to keep the participants in a state of hyperhydration 6 h after ingesting the drink when they consumed either 150% or 200% of their sweat loss. The excess would eventually be lost by urine production or by further sweat loss if the individual resumed exercise or moved to a warm environment. Calculated plasma volume changes indicated a decrease of approximately 5.3% with dehydration. At the end of the study period, the general pattern was for the increases in plasma volume to be a direct function of the volume of fluid consumed, with the increase tending to be greater for those individuals who ingested the high sodium drink.

Although other studies have also shown the importance of drinking a larger volume of drink than the sweat volume lost (Mitchell *et al.*, 1994), an interaction between sodium intake, volume intake and whole-body rehydration has not always been reported (Mitchell *et al.*, 2000). However, it is likely that in this study the length of time participants were observed after rehydration may not have been sufficient to discern the urine production response to the treatments. Additionally, evidence has recently emerged suggesting that the rate of drinking a large rehydration bolus can have important implications for the physiological handling of the drink (Archer and Shirreffs, 2001; Kovacs *et al.*, 2002). Drinking a large volume of fluid has the potential to induce a greater decline in plasma sodium concentration and osmolality, which, in turn, have the potential to induce a greater diuresis.

Food and fluid consumption

In many cases, there may be opportunities to consume solid food between exercise bouts; this should be encouraged unless it is likely to result in gastrointestinal disturbances. Maughan *et al.* (1996) examined the role of solid food intake in promoting rehydration from a 2.1% body mass sweat loss with consumption of either a solid meal plus flavoured water or a commercially available sports drink. The volume of fluid in the meal plus water was the same as the volume of sports drink consumed. The amount of urine produced after food and water ingestion was almost 300 ml less than that when the sports drink was consumed. Plasma volume decreased by approximately 5.4% with dehydration and was restored to the same extent with both rehydration processes. Although the quantity of water consumed with both rehydration methods was the same, the meal had a greater electrolyte content (63 mmol Na^+ and 21 mmol K^+ *vs* 43 mmol Na^+ and 7 mmol K^+) and it is most probable that the greater efficacy of the meal plus water treatment in restoring whole-body water balance was a consequence of the greater total cation content causing a smaller volume of urine to be produced. Subsequent studies have also highlighted a role for food products in post-exercise fluid balance restoration (Ray *et al.*, 1998).

Beverage palatability and voluntary fluid intake

In most scientific studies in this area, a fixed volume of fluid is consumed; in everyday circumstances, however, intake is determined by the interaction of physiological and psychological factors. When the effect of palatability and solute content of beverages in promoting rehydration after sweat loss was studied (Wemple *et al.*, 1997), participants drank 123% of the sweat volume losses with flavoured water and 163% and 133% when the solution had 25 and 50 $mmol \cdot l^{-1}$ sodium. Three hours after starting the rehydration process, the participants had a better whole-body hydration status after drinking the sodium-containing beverages than the flavoured water. In a similar study (Maughan and Leiper, 1993), participants drank a greater volume of sports drink (2492 ml) and orange juice/lemonade mixture (2488 ml) than of either water (1750 ml) or an oral rehydration solution (1796 ml) reflecting their taste preferences. As expected, urine output was greatest with the low electrolyte drinks that were consumed in the largest volumes (the sports drink and the orange juice/lemonade mixture), and was smallest after drinking the oral rehydration solution. These studies demonstrate the importance of palatability for promoting consumption, but also confirm earlier results showing that a moderately high electrolyte content is essential if the ingested fluid is to be retained in the body. The benefits of the higher intake with the more palatable drinks were lost because of the higher urine output. Other drink characteristics, including carbonation, influence drink palatability and therefore need to be considered when a beverage is being considered for effective post-exercise rehydration (Passe *et al.*, 1997).

Intravenous rehydration

Intravenous fluid therapy has, in the last few years, been used as a rehydration method for dehydrated athletes in cases where it has not been necessary for medical treatment. The argument for its use is based upon perceived health, performance or other benefits over and above those that can be achieved with oral rehydration. In the scientific literature, comparisons have been made between oral and intravenous rehydration from very moderate dehydration on subsequent exercise performance and found no difference in exercise capacity (Nagra, 1998). Similarly, a series of papers reporting a study investigating partial rehydration (from approximately 4% to 2% dehydration) concluded that subsequent exercise performance was better when rehydration occurred irrespective of whether it was by mouth or intravenously (Casa *et al.*, 2000a,b; Maresh *et al.*, 2001). These authors reported that during the subsequent exercise, rectal temperature was lower and heart rate tended to be lower when rehydration had been achieved orally. There is, however, evidence that the sensation of thirst remains higher after partial intravenous rehydration than after partial oral rehydration (flavoured drink with 77 $mmol \cdot l^{-1}$ Na^{+}), which is more likely to promote subsequent drinking as required (Riebe *et al.*, 1997). In combination, these studies provide data both to support and refute intravenous rehydration, particularly when a subsequent exercise bout is to be performed.

One potentially practical use of selecting intravenous rehydration over drinking is the case in which significant dehydration (>2% body mass) is incurred over a short-time frame and with a brief rest period before subsequent exercise. For example, a trained and heat-acclimated athlete can sweat at a rate in excess of 2 $l \cdot h^{-1}$. Assuming that one of two or more daily training sessions lasts 2 h and 50% of sweat losses are replaced during exercise, a 2-litre deficit occurs and 3–4 litres of fluid must be consumed (150–200% of deficit) to fully restore fluid balance (Shirreffs *et al.*, 1996) before the next workout. The challenge to rehydrate orally and then perform again could, when limited time is available, be better achieved with intravenous rehydration.

Conclusions

For a person undertaking regular exercise, any fluid deficit that is incurred during one exercise session can potentially compromise the next exercise session if adequate fluid replacement does not occur. As such, fluid replacement after exercise can frequently be thought of as hydration before the next exercise bout. However, additional specific issues in this area include ensuring euhydration before exercise and inducing a temporary hyperhydration with sodium salts or glycerol solutions.

Complete restoration of fluid balance after exercise is an important part of the recovery process, and becomes even more important in hot, humid conditions. If a second bout of exercise has to be performed after a relatively short interval, the rate of rehydration is of crucial importance. Rehydration after exercise requires not only replacement of volume losses, but also replacement of the electrolytes, primarily sodium, lost in the sweat. Daily sweat and sodium losses vary widely among individuals and depend on many factors, including the environment, diet, physical fitness and heat acclimation status. However, where sweat losses are large, the total sodium loss will generally also be high. For example, a daily loss of 10 litres of sweat at a sodium concentration of 50 $mmol \cdot l^{-1}$ (normal range of 10–80 $mmol \cdot l^{-1}$) amounts to about 29 g of sodium chloride. A moderate excess of salt intake would appear to be beneficial as far as hydration status is concerned without any detrimental effects on health, provided that fluid intake is in excess of sweat loss and that renal function is not impaired. Any excess sodium ingested will be excreted in the urine as the kidneys restore equilibrium. Drinks intended specifically for rehydration should, therefore, probably have a higher electrolyte content than drinks formulated for consumption during exercise.

The addition of an energy source does not appear necessary for rehydration, although a small amount of carbohydrate may improve the rate of intestinal uptake of sodium and water, and will improve palatability. Where sweat losses are high, rehydration with carbohydrate solutions has implications for energy balance (e.g. 10 litres of soft drinks will provide approximately 1000 g of carbohydrate, equivalent to about 17,000 kJ or 4000 calories). The volume of beverage consumed should be greater than the volume of sweat lost to allow for the ongoing obligatory urine losses, and palatability of the beverage is a major issue when large volumes of fluid have to be consumed.

Intravenous rehydration after exercise has been investigated to a lesser extent and its role for fluid replacement in the dehydrated but otherwise well athlete remains open to discussion.

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